GEOMAGNETIC DISTURBANCES

By

Masahisa Sugiura

NASA - Goddard Space Flight Center

Greenbelt, Maryland

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1. Introduction

It was in 1741 that Andreas Celsius of Upsala and his colleague Hiorter first discovered magnetic disturbances accompanying the aurora. By correspondence with George Graham of London, a pioneering observer of geomagnetic variations, Celsius found that the magnetic disturbances associated with the aurora in Sweden are simultaneously observed in England. These early discoveries are not only of historical interest, but are directly related to two important aspects of geomagnetic disturbances: namely, that the largest magnetic disturbances are closely associated with the aurora and that magnetic disturbances are essentially of global rather than of regional character. Because of this latter nature the study of geomagnetic disturbances requires a world-wide coverage of observations from the equatorial to the polar regions. Moreover, close associations of geomagnetic disturbances with the aurora, precipitation of particles, and other disturbance phenomena greatly extend the scope of the study of this subject. The recent technological advances have made possible the measurements of the magnetic fields, plasmas, and high energy particles in space, and observational data upon which the physical interpretation of geomagnetic disturbances can be based are rapidly accumulating. However, the complexity of geomagnetic disturbance phenomena makes our understanding far from being complete.

2. A survey of time variations in the geomagnetic field

2a. Magnetic variation on quiet days

The solar radiation in the X-ray to ultra-violet range ionizes the constituents of the upper atmosphere, resulting in the formation of the

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ionosphere. Though the electron density is greatest in the F layer with a peak electron density at about 250 km height, the E layer below is more electrically conducting than the F layer due to the effect of the earth's magnetic field. The upper atmosphere is in constant motion due mainly to the solar heating and the gravitational forces of the moon and the sun. In the presence of the vertical component of the earth's field, horizontal motions in the E layer generate electric currents as in a dynamo. The existence of this global system of electric current is continuous, and the earth revolves underneath, thus producing the diurnal magnetic variation at any fixed point on the earth. The variation is denoted by Sq, S for solar and q for quiet, as it represents the variation observed on a typical magnetically quiet day. The amplitude of Sq varies with latitude, season, and sunspot cycle, but it is roughly 20 to 50 gammas in midlatitudes.

2b. Solar flare effect (a minor disturbance)

Solar flares emit intense X-rays in the wavelength range from 2 to 8 Å which greatly increase the ionization in the D region. The emission contains an appreciable amount of X-rays of longer wavelengths than these, and the ionization in the region where the Sq current flows is also increased, thereby enhancing the magnetic variation Sq. This disturbance is called a solar flare effect, and because of the typical appearance of the magnetogram traces, particularly in the horizontal component, at the time of such an event it is frequently referred to as a crochet. The solar flare effect is limited to the sunlit hemisphere and is largest, as may be expected, near noon. Though small as a magnetic disturbance, the increased ionization in the D region causes heavy absorption of radio waves, interrupting long distance radio communication via the ionosphere; this ionospheric effect is called a sudden ionospheric disturbance or SID. Solar flare effects usually last for 10 to 15 minutes. Magnetic solar flare effects are augmented in a narrow belt of a few degrees width over the dip equator where the normal Sq variation itself is enhanced. Changes in the magnetic field in solar flare effects are typically several gammas to 20 gammas at midlatitudes, and thus they are only minor magnetic disturbances, but are of considerable theoretical interest.

2c. Major disturbances

In high latitudes the magnetic conditions are disturbed to varying degrees almost nightly. These polar disturbances, as they are commonly called, are discussed in detail in 3. Polar disturbances of moderate intensity that frequently occur in high latitudes do not produce any major disturbance in middle and low latitudes. However, even at these lower latitudes magnetic disturbances of considerable intensity are experienced from time to time; such disturbances are called magnetic storms. They are the severest of magnetic disturbances and affect the entire globe. During a magnetic storm the polar disturbances of the type discussed in 3 are greatly intensified, and their effects extend to lower latitudes. Phenomenological characteristics of magnetic storms are discussed in 4. A summary of theoretical interpretations of polar disturbances and magnetic storms is given in 5.

3. Polar disturbances

3a. Magnetic bays

At stations in high latitudes magnetic disturbances occur most frequently near geomagnetic midnight; geomagnetic midnight at a station is defined as the time when the sun is in the meridian opposite to that containing the station and the geomagnetic axis. Before geomagnetic midnight the disturbance is typically positive (i.e. northward) in the horizontal component, H; while after geomagnetic midnight it becomes a negative (southward) change in H of larger amplitude than the positive change. These positive and negative changes are often referred to as positive and negative bays, respectively. The beginning of a negative bay is sometimes very abrupt, and its decay is slower. The total duration of a negative bay ranges roughly from one to a few hours. Such a disturbance may be repeated several times in the course of a night. The severity of the disturbance varies greatly from one case to another; the amplitude in H in a moderate negative bay is roughly several hundred to one thousand gammas, but in a severe case the amplitude may reach two or three thousand gammas. While the gross change in a negative bay is a large decrease in H, rapid fluctuations of various amplitudes and periods are observed in all three components. Positive bays are smaller and contain much less fluctuations than negative bays.

These bay disturbances are most intense along two narrow zones, one in each hemisphere, at about 65° geomagnetic latitude where the occurrence of auroras is statistically a maximum; these zones are called the northern and southern auroral zones, each of which is nearly of oval shape with its center approximately at the north or the south geomagnetic pole. In the polar cap, namely, in the region inside the auroral zone, the disturbances are less intense than at the auroral zone.

3b. Auroral electrojets

The spatial distribution of the magnetic disturbance of a negative bay indicates that it is due to a concentrated westward current flowing in the ionosphere along the auroral zone. When a negative bay is observed in the local time zone east of the geomagnetic midnight meridian, a positive bay is usually observed to the west of that meridian. This latter is attributed to an eastward current flowing along the auroral zone in the corresponding time zone. These currents are highly concentrated and are called the auroral electrojets. The westward electrojet flowing over the post-midnight zone is much more intense than the eastward electrojet. The electrojet currents close their circuits mostly by a return current over the polar cap and partly by currents flowing over moderate and low latitudes.

3c. Current system

Figure 1 shows an idealized current system for the polar disturbance; the current system is viewed from above the geomagnetic north pole, and the earth rotates underneath the current system. As has been mentioned above, such a disturbance current system develops and decays in a few hours, and such an event may be repeated several times in 24 hours during which the earth completes one revolution under the current system.

Although these views have been held generally (e.g., Chapman and Bartels, 1940; Vestine et al. 1947; Sugiura and Heppner, 1965), Akasofu (1965) has proposed that the auroral electrojet is westward everywhere in a somewhat distorted, but complete oval circuit and that a positive bay which has been thought to be due to an eastward electrojet is really due to a leakage current from the westward electrojet. However, the observational evidence does not appear to be sufficient to substantiate the latter view.

3d. Disturbances at magnetically conjugate areas

Polar disturbances are generally observed simultaneously at magnetically conjugate areas, namely, two areas one in each hemisphere, that are connected by lines of force of the earth's permanent magnetic field. Frequently, magnetic variations at a pair of conjugate areas are similar even to minor details. This conjugate characteristic has an important implication in the theoretical interpretation that will be given in 5.

3e. Relation with the aurora

In the auroral zones magnetic bays are closely related to the aurora. Before geomagnetic midnight, that is, during the phase in which a magnetic positive bay is occurring, homogeneous quiet arcs are usually observed, and simultaneously with the rather abrupt onset of a negative bay the auroral arcs suddently become brilliant and break up into rayed arcs and bands. This is the most active phase of the aurora, and after this phase the aurora takes various forms such as draperies and diffuse surfaces, and becomes weaker in intensity as the magnetic disturbance subsides. This represents a typical cycle of events in the auroral zone, but when the intensity of disturbance is great, the features are more complex. On an average active night the basic cycle described above may be repeated a few times in the course of the night.

3f. Over the polar cap

With increasing latitude beyond the auroral zone the association of magnetic disturbance with auroral activity becomes less distinct, and above about 80° geomagnetic latitude the correlation may even appear to be negative. As is shown in the idealized disturbance current system in Figure 1 the current over the polar cap is very nearly uniform when the eastward and westward electrojets develop in the auroral zone. Besides the magnetic disturbances associated with auroral electrojets there are disturbances that occur in the region near the noon meridian; this region of daytime disturbance is indicated in Figure 1 by a shaded area. These disturbances are not so large as those related to electrojets, and consist of irregular fluctuations of the magnetic field. They may be due to hydromagnetic waves propagating down the lines of magnetic force from a region near the magnetosphere boundary.

4. Magnetic storms

4a. Occurrences of magnetic storms

It has been frequently observed that when an intense solar flare occurs on the sun the earth's magnetic field is severely disturbed a few days later. Such a disturbance is called a magnetic storm. However, there are magnetic storms that cannot be traced back to any pronounced flares on the sun. These storms tend to recur with a 27 day period, and have been named by Bartels M region storms, ascribing their origin to an unidentified region M on the sun. It is now thought that the emission of hot plasma from an active region on the sun can last over a period of many solar rotations and that consequently the beam of hot plasma sweeps past the earth several times with the sun's rotation period of 27 days. The occurrence of these recurrent storms appear to be a notable feature during years of low solar activity; while in the years near a maximum of solar cycle (of 11 years) occurrences of magnetic storms directly associated with large solar flares become more frequent.

4b. Storm sudden commencement and the initial phase

Magnetic storms, particularly those occurring after a solar flare, often begin with a sudden commencement, which is characterized by an abrupt worldwide increase of the horizontal component of the geomagnetic field; a typical magnitude of this increase in low latitudes is a few tens gammas. Figure 2 shows an example of records taken at several stations during a magnetic storm; the sudden commencement of the storm is marked with a symbol SC.

After a sudden commencement the horizontal component H often remains increased above its pre-storm level for a few hours. This phase is called the initial phase, and is a typical feature in low and middle latitudes. In high latitudes a severe disturbance may begin immediately after the sudden commencement and mask the increase in H in the initial phase. Even in low latitudes some storms do not follow the average morphological pattern; the initial phase may be completely lacking or may appear to last for an extended period without any large disturbances.

4c. Main phase

The initial phase is followed by the main phase which is a large worldwide decrease in H. The maximum depression in H is reached in several hours to one day from the sudden commencement, and its magnitude varies from a few tens to a few hundred gammas. The main-phase decrease in H is roughly symmetric about the geomagnetic axis and represents an approximately uniform field surrounding the earth. Polar disturbances — polar substorms as they are sometimes called — increase their activity after the sudden commencement. These polar substorms occur in bursts, and although they are of much greater intensity than the more frequent polar bays discussed in 3a, their characteristics are similar to the latter. The large decrease in the magnetic field in the main phase is followed by a slow recovery toward the normal level. This recovery phase may take a few days to ten days, or possibly even longer. On an average quiet day there is an almost linear increase in H by several gammas per day because of this slow recovery from the preceding magnetic storm, or storms.

It is found convenient to decompose the magnetic storm variation into two parts, the storm-time variation Dst and the disturbance longitudinal inequality DS. At any given storm-time (i.e., the time reckoned from the sudden commencement) the former is the average of the disturbance field over longitude, and hence it is a function of storm-time and geomagnetic latitude. DS is the deviation of the storm field from Dst, and thus it is a function of storm-time, longitude, and geomagnetic latitude. The increase in H in the initial phase and the major decrease of the same component during the main phase that are mentioned above are the notable features of Dst, and the effects of the polar substorms constitute the main part of DS. Statistically, the maximum activity in DS precedes that in Dst. The current pattern shown in Figure 1 may be thought to be a typical current system for DS.

5. Interpretations of geomagnetic disturbances

5a. Preliminaries: The solar wind and the magnetosphere

Before presenting physical interpretations of polar disturbances and magnetic storms of which the major morphological characteristics have been described above, it appears to be appropriate to give a brief summary of the physical state of the earth's environment under the normal condition. The recent plasma measurements by space probes and satellites have established that there exists a continuous outward flow of plasma from the sun, the plasma consisting mainly of hydrogen ions and electrons, and some helium ions, and that the hydrogen ions are generally of speeds of 300 to 700 km/sec and of density about 2 to 10 per cm^3. This flow of plasma from the sun is now called the solar wind, the existence of which was first predicted by Biermann (1955) from his study of the acceleration of comet tails, and which was theoretically deduced by Parker (1957) before the actual measurements by Lunik II (Gringauz et al., 1960), Explorer X (Bonetti et al., 1963), Mariner II (Neugebauer et al., 1962), and IMP I (Bridge et al., 1964).

The solar wind confines the geomagnetic field in a cavity surrounding the earth, and the region inside this cavity is called the magnetosphere. At the boundary of the magnetosphere the plasma pressure of the solar wind is balanced by the magnetic pressure of the earth's field inside the magnetosphere. The boundary is roughly hemispherical on the sunward side, and its distance from the earth is about 10 earth-radii. The solar wind carries a magnetic field of the order of a few to ten gammas. It is thought that because of the presence of this magnetic field the plasma, though practically collisionless, behaves like a fluid over dimensions larger than the Larmor radius of the ions which is of the order of 10^3 km; and the speed of the solar wind is supersonic with respect to the Alfvén speed, the Mach number being 5 to 20. Thus Kellogg (1962) and Axford (1962) predicted a presence of a standing shock wave in front of the magnetosphere boundary. The existence of such a shock wave a few earth-radii upstream has been confirmed by the measurements made by the satellite IMP I (Ness et al., 1964). In the transition region between the shock front and the magnetosphere boundary the magnetic field is turbulent, and the particle motions are isotropic; the latter feature contrasts with the unidirectional flow of the plasma outside the shock front.

On the opposite side of the magnetosphere, namely, on the side facing the antisolar direction, the lines of magnetic force originating from the polar caps are stretched out to great distances probably to a few hundred earth-radii or to even greater distances; this region is called the magnetosphere tail, or simply, the geomagnetic tail (Ness, 1965). The magnetic field in the magnetosphere tail is directed toward the earth above the geomagnetic equator and is directed away from the earth below it. Within a relatively thin sheet at the equator the magnetic field is near zero; this region is referred to as the neutral sheet (Ness, 1965). These features of the magnetosphere, which are relevant to geomagnetic disturbances, are summarized in Figure 3.

5b. Emission of hot plasma from the sun

We have already mentioned in 2b that a solar flare emits X-rays and ultra-violet rays besides the radiation in visible light. In longer wavelengths there is an emission of radio waves of several distinct types; some of these radio emissions are thought to be radiation from high energy electrons. The energy in the strong magnetic fields in the flare region is partially converted into kinetic energy of electrons and hydrogen ions (and some helium ions) resulting in solar cosmic rays that are observed on the earth following the visible solar flare. Hot plasmas are also emitted from the flare region and upon reaching the earth they cause terrestrial magnetic disturbances. In a series of papers Chapman and Ferraro (1931, 1932, 1940) and Ferraro (1950) discussed in detail the interaction of such a plasma stream with the geomagnetic field, and concluded that a cavity would be formed in the solar plasma stream by the geomagnetic field. As we have seen in 5a, the containment of the geomagnetic field in such a cavity is now known to be a permanent feature not limited to times of solar-flare emissions of plasma.

5c. Compression of the magnetosphere

An important effect of the arrival of a hot solar-flare plasma at the earth is a compression of the already existing geomagnetic cavity and hence the magnetosphere. This compression is transmitted from the magnetosphere boundary to the earth by hydromagnetic waves and causes the sudden increase in H that has been discussed in 4b. Since the magnetosphere will remain compressed until the increased pressure of the solar plasma is relieved, H will remain increased after the sudden commencement; this corresponds to the initial-phase increase in H. Because of the sharpness of the rise in H at the time of sudden commencement Gold (1955) suggested that the sudden commencement represents the arrival of a shock wave created by a solar exraption. Parker (1961) also concluded from his theory of solar wind that there would be a shock wave generated by a supersonic blast wave from a solar flare. In these models an increase in the plasma pressure behind the shock wave results in a compression of the magnetosphere. Existence of shock waves in the interplanetary space has been shown by Mariner II (Sonett et al., 1964). The question of whether a sudden commencement represents the arrival of a solar plasma or a shock wave is not as yet settled.

5d. Dst and a ring current

The decrease in H can be accounted for by a ring-shaped westward current encircling the earth. Such a suggestion was made by Störmer as early as 1911, anda model ring current has been investigated extensively by Chapman and Ferraro (1931). More recently Singer (1957) conceived a ring current as being due to drifting motions of ions trapped in the geomagnetic field. Subsequently searches have been made to identify the trapped particles that are responsible for the main phase Dst. However, the ring current has been found to be evasive to detection of its location by measurements of its magnetic field and its particles. It is now thought that the (still hypothetical) ring current consists of mainly protons and some electrons of energies of 10 to 100 kev and that it must lie at a distance of 2 to 4 earth-radii from the earth's center. How the particles composing the ring current are injected to the inner region of the magnetosphere, or alternatively, how the particles existing in the magnetosphere are energized to form a ring current is still an open question. Akasofu (1964) suggested that a ring current might be formed by neutral hydrogen atoms emitted by a solar flare together with a plasma; the neutral hydrogen would penetrate deeply into the magnetosphere and become charged by a charge exchange process.

5e. The DS current system

There seems to be little doubt that the major part of the DS current, such as shown in Figure 1, actually flows in the ionosphere. Since the ionospheric conductivity in the auroral zones is greatly increased by the bombardment of high energy particles, some authors (e.g., Fukushima,

1953) have considered the possibility that the DS current system might be generated by a dynamo mechanism as in Sq. However, this is not likely to be the case for several reasons. For instance, for such a mechanism to be effective, wind velocities must be unreasonably high; the large rapid fluctuations often observed in DS are difficult to explain by the dynamo-theory; as has been mentioned, variations in DS are similar at magnetically conjugate regions while those in Sq do not show this characteristic.

An alternative theory seeks a mechanism in the magnetosphere, the essential part of the theory being a creation of large scale electric fields there. Several different models have been presented for such electric fields (Vestine, 1960; Chamberlain, 1961; Kern, 1961; Fejer, 1963). If space charges are set up in the magnetosphere by differential drifting of ions and electrons or by some other means, the electric field created will be transported to the ionosphere along the lines of magnetic force due to the large conductivity along them, and drive a system of Hall currents in the ionosphere. In the theory presented by Fejer (1963) the proton belt observed by Explorer XII (Davis et al., 1963) plays an important part in creating the necessary space charge distribution for the electric field. Although these theories account for the statistically derived average features of DS, they encounter difficulties in explaining more detailed behaviors in individual events.

Recent observations made by IMP I in the geomagnetic tail have revealed a close correlation between magnetic disturbances in the polar regions and the magnetic field in the tail (Behannon and Ness, 1965). There appears to be little doubt that the geomagnetic tail holds the key to the problem of polar disturbances and the aurora.

Piddington, who predicted (1960) the geomagnetic tail by his theory of a frictional interaction between the solar wind and the plasma in the magnetosphere, has investigated various consequences of this interaction in an attempt to explain geomagnetic disturbance phenomena (1960, 1963, 1964, 1965).

5f. Convection in the magnetosphere

Using an analogy with a similar problem in fluid dynamics Axford and Hines (1961) proposed that due to a viscous-like interaction the plasma in the surface layer of the magnetosphere is driven downstream along the boundary. At the time their theory was presented it was not certain whether the magnetosphere was closed or open in the rear, and they took a closed magnetosphere model. They argued that the downstream flow of plasma in the surface layer must return from the tail end of the magnetosphere to the interior thus generating a convection in the magnetosphere. Although the existence of a long tail is now well established, their concept of a convection in the magnetosphere is of considerable theoretical interest and is shown in Figure 4. Axford and Hines indicated that many of the polar disturbance phenomena can be explained by their model.

5g. Magnetic field lines from the polar caps

It has been recognized that even on extremely quiet days there is a current system in the polar cap region resembling that of DS (Nagata and Kokubun, 1962). Dungey (1961) suggested that the magnetic field lines originating in the polar regions might become connected with the field lines of the interplanetary magnetic field and are blown downstream by the solar wind. The feet of these polar field lines are thus continuously being pulled from the sunward side toward the night side. The electrons in the E region of the ionosphere are dragged by the field lines thus producing an electric current flowing in the direction opposite to that of the motion of the field lines. This is equivalent to saying that an electrostatic field is created across the polar cap and that a Hall current is driven in the direction described above.

This idea has been further advanced by Axford, Petschek, and Siscoe (1965). According to the model proposed by these authors, the polar magnetic field lines that are connected to the interplanetary field lines are pulled back behind the earth to great distances before being separated from them; when separated from the interplanetary field lines the northern and southern polar field lines are reconnected in pairs and return to the day side along the circumference of the polar cap. In the rear of the magnetosphere the polar field lines are stretched out to large distances forming a long tail. The electrostatic potential across the polar cap is transported to the tail, the electric field there being in the direction transverse (east to west) to the length of the tail. This electric field drives the field lines in the tail toward the equatorial plane, where oppositely directed field lines above and below this plane are annihilated. The thin layer at the equatorial plane corresponds to the observed neutral sheet.

Near the neutral sheet the magnetic field is weak, and the magnetic pressure is compensated by the plasma pressure. In this region large fluxes of high energy electrons have been observed by IMP I (Anderson, 1965). Such high energy electrons in the geomagnetic tail may be responsible for some of the polar disturbances.

6. Geomagnetic activity indices

There are several geomagnetic activity indices that are in use to classify days according to magnetic activity and to compare geomagnetic disturbances with other disturbance phenomena observed on the ground or in space. The most widely used is the magnetic K index. At each magnetic observatory every 3-hour interval in universal time is assigned a numerical index K varying from 0 to 9; the scale is based on the largest deviation in the three components during each 3-hour interval from the normal variations defined for that observatory. The scale is adjusted relative to those for other observatories so that the distribution of occurrences of each K value is similar at different observatories.

To define a planetary activity index the K indices from twelve selected observatories in a geomagnetic latitude range $47.^{\circ}7$ to $62.^{\circ}5$ are averaged. The index so defined for each 3-hour interval of universal time is called the Kp index. When expressed on a linear scale, Kp gives another index called ap. The Kp index is essentially an index representing the degree of magnetic disturbance in the auroral zone as measured by the magnetic field from the return current of the auroral electrojets. However, when the auroral electrojets move equatorward in great storms some of these observatories may be directly under the influence of the electrojets. Some attempts are being made to represent the Dst variation, as a continuous function of universal time, and the intensity of the auroral electrojets more directly.

There are other internationally adopted magnetic indices such as C, the daily magnetic character figure on a scale of 0, 1, and 2, and the U measure that represents day-to-day variability of the magnetic field. The definitions of these indices, their standardization and publication have been due to the life-long dedicated work of Bartels.

References. The following books, review articles, and some papers cover most of the references for the present article.

* Chapman, S., 1962, Solar plasma, geomagnetism and aurora, Geophysics edited by C. DeWitt, J. Hieblot, and A. Lebeau, pp. 373-502, Gordon and Breach, New York.

* Chapman, S., and J. Bartels, 1940, Geomagnetism, Vols. 1 and 2, Oxford Univ. Press, Oxford.

* Hess, W. N., editor, 1965, Introduction to Space Science, Gordon and Breach, New York; in particular, Ch. 1, The earth's magnetic field, by M. Sugiura and J. P. Heppner, pp. 5-92, and Chs. 4, 8, and 9.

Ness, N. F., 1965, The earth's magnetic tail, Jour. Geophys. Res., Vol. 70, 2989-3005.

* Piddington, J. H., 1964, Geomagnetic storms, auroras and associated effects, Space Sci. Rev., Vol. 3, 724-780.

Sugiura, M., and S. Chapman, 1960, The average morphology of geomagnetic storms with sudden commencement, Abh. Akad. Wiss. Göttingen, Math. - Phys. Kl., Sond. Nr. 4, pp. 53.

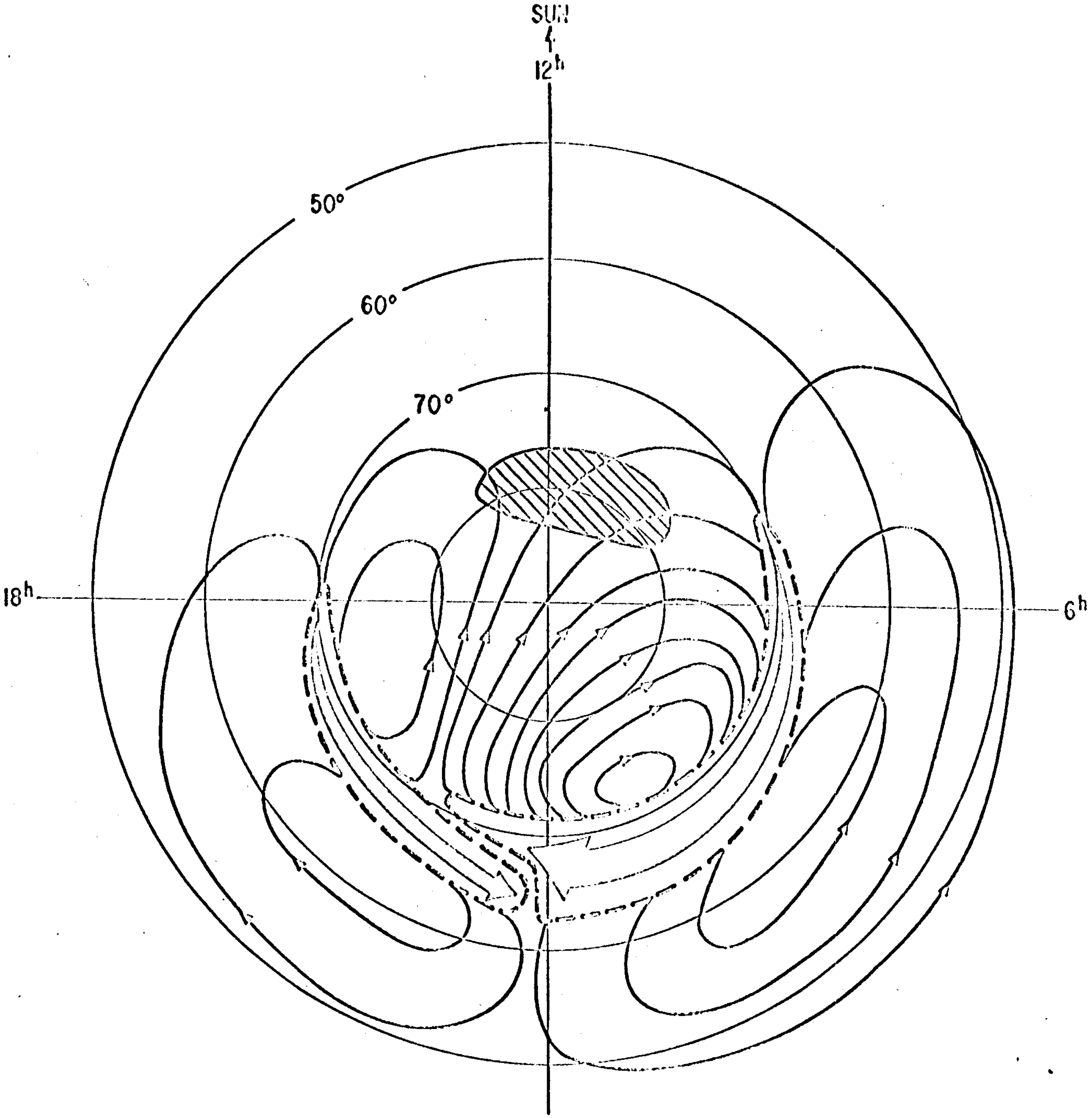
Figures

Figure 1. An illustrative current system for polar magnetic disturbances, viewed from above the north geomagnetic pole. Dark arrows indicate auroral electrojets. Concentric circles show geomagnetic latitude circles. The shaded area on the sunward side near 80° geomagnetic latitude represents the daytime field agitation. (After Sugiura and Heppner, 1965.)

Figure 2. Magnetograms taken at different latitudes during a magnetic storm. Note the sudden beginning marked SC for all stations, the initial phase and the main phase observed at Honolulu and Huancayo, and the polar disturbance as seen at College. (After Sugiura and Heppner, 1965.)

Figure 3. Illustration of the topology of the geomagnetic field as determined by the satellite IMP I. The earth is at the origin, and the sun is to the left. Scales on the x and y axes are in earth-radii. (After Ness, 1965.)

Figure 4. A schematic picture of the convective motions in the magnetosphere proposed by Axford and Hines; the convection is generated by the viscous-like interaction between the solar wind and the surface of the magnetosphere and is somewhat distorted due to the rotation of the earth. (After Axford and Hines, 1961.)



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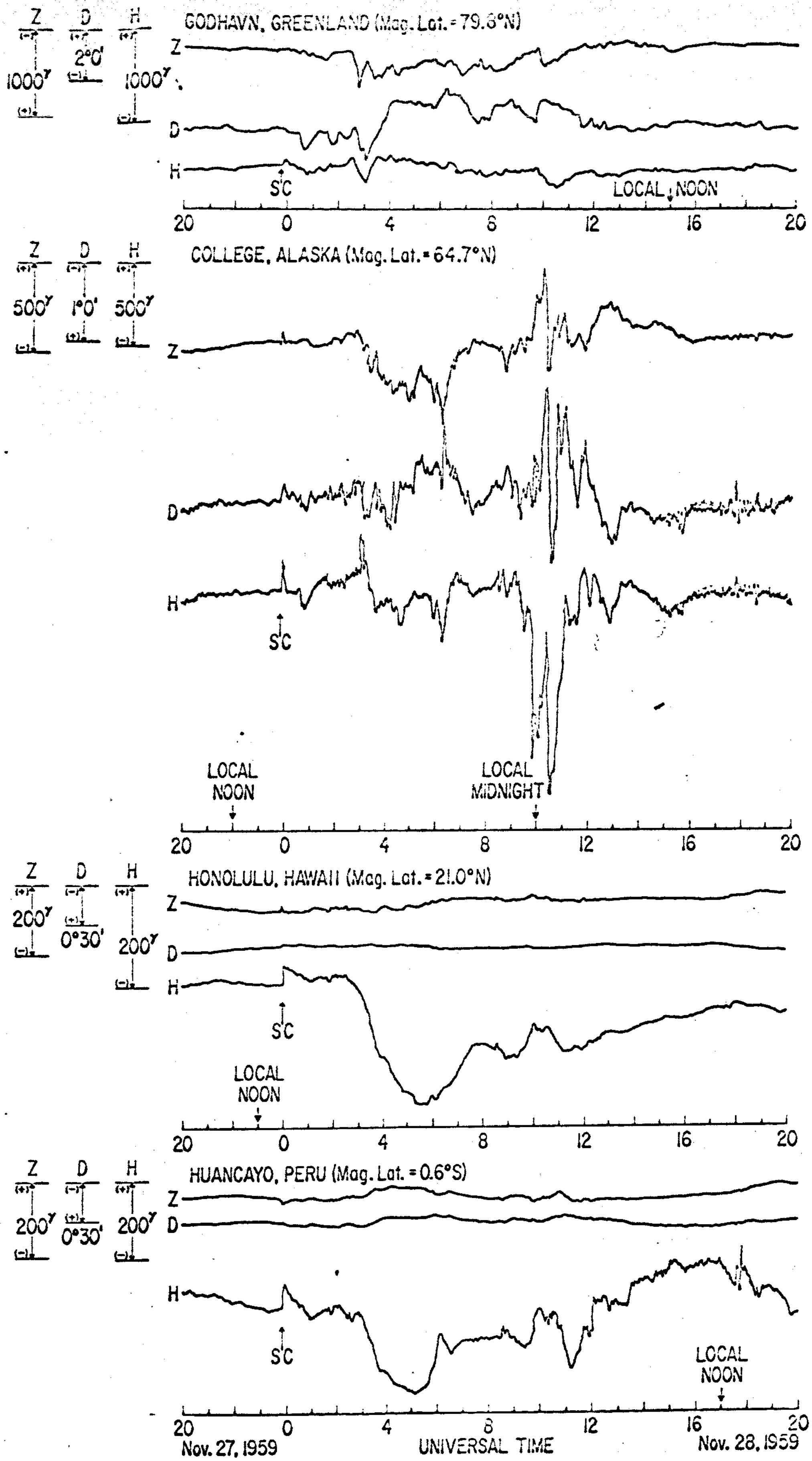

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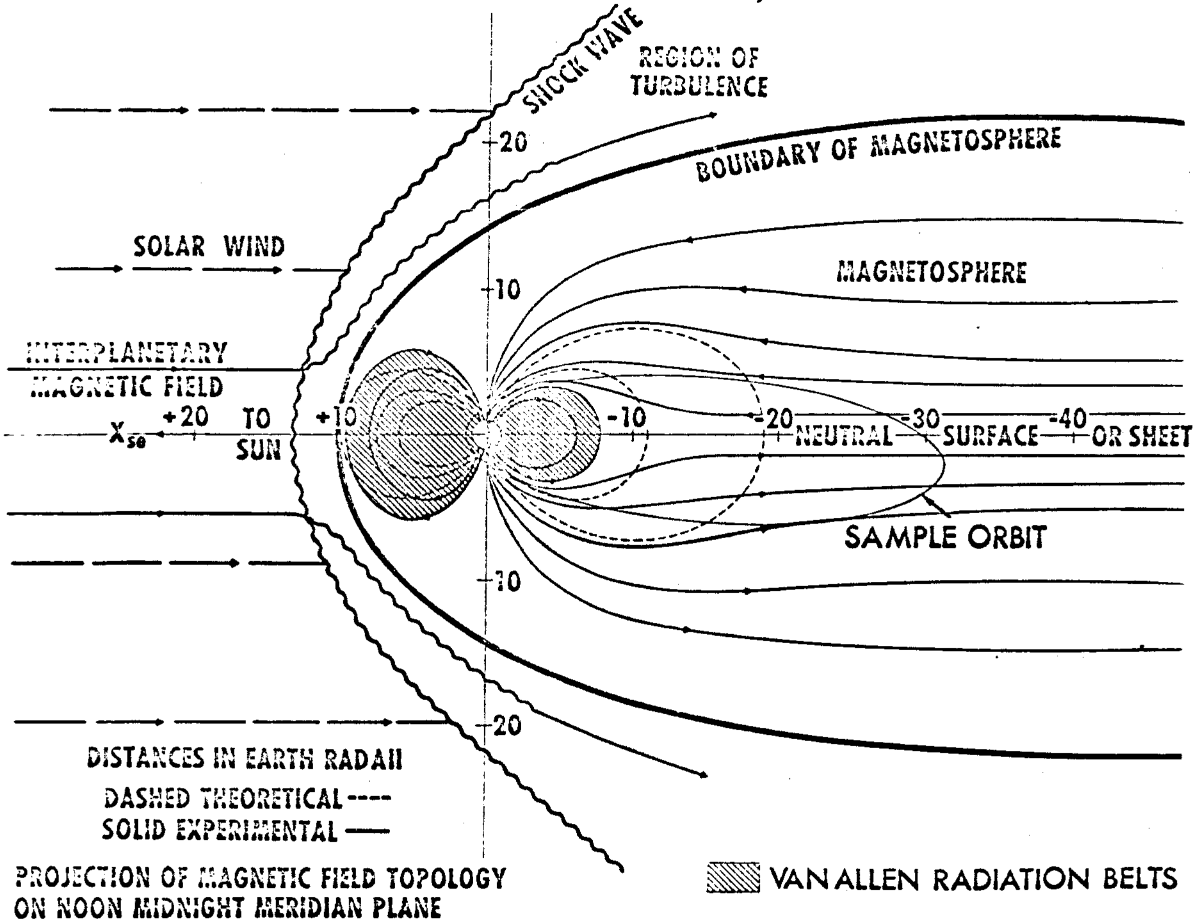
RESULTS OF IMP-1 MAGNETIC FIELD EXPERIMENT

(11/27/63 TO 5/31/64)



contours, addin [illegible] values of potential at a number of points throughout the field, and dr[illegible]w contours of constant total potential. The assignment of values to [illegible] original contours is straightforward in the case of the rotational system, at least for the undistorted portions of the geomagnetic field, since the angular velocity and the field are known. The corresponding assignment for the counter-rotating geomagnetic tail and for the convective system is rather arbitrary in the absence of a detailed analysis, although the direction of increasing potential is predetermined by the direction of V required. Despite this arbitrariness, the general trend of the resultant flow pattern is quite unambiguous; it is depicted for one specific case in Fig. 5. The principal feature to be noted is that the ionization convecting inward on the nighttime

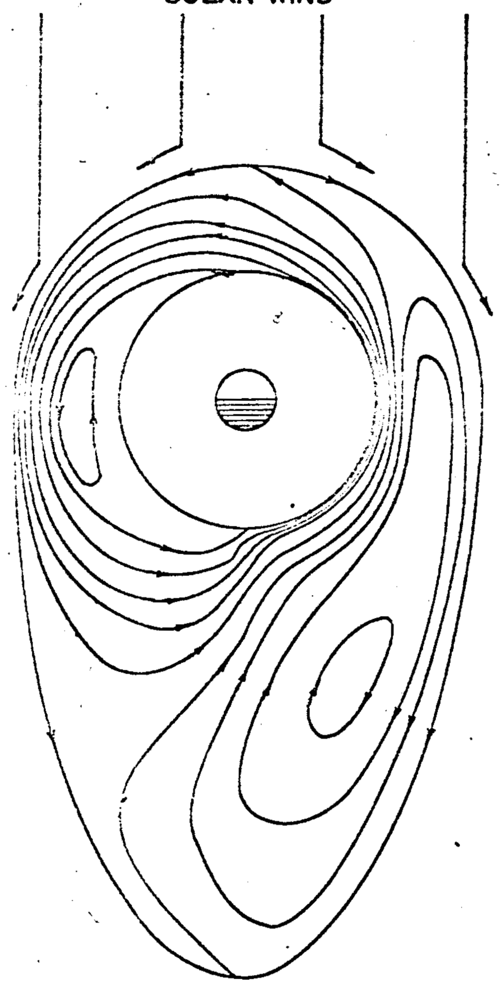


FIG. 5. A composite picture obtained by superimposing the equipotentials of Figs. (2) and (3), showing the type of motion to be expected in the presence of rotation and a viscous-like interaction between the solar wind and the surface of the magnetosphere.